Assimilation of Three-Dimensional Phase-Resolved Wave-Field Data Using an Efficient High-Order Spectral Method

Dick K.P. Yue
Department of Ocean Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
phone: (617) 253- 6823 fax: (617) 258-9389 email: yue@mit.edu

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LONG-TERM GOAL

The long-term goal is to develop a robust and efficient computational tool for direct phase-resolved large-scale simulations of nonlinear ocean wave-field evolutions under offshore and coastal environments including realistic effects due to nonlinear wave-wave interactions, variable current, wave-breaking dissipation, bottom reflection and refraction, and wind-wave interactions.

OBJECTIVES:

The specific scientific objectives of this program are to:

1. Extend and apply an existing phase-resolved simulation program, a powerful high-order spectral method (HOS) for nonlinear wave-wave interactions, to assimilate realistic ocean wave-field data and to predict long-time evolutions of such nonlinear wave-fields

2. Obtain realizable initial wave-fields for phase-resolved simulations from either of the following: (i) multiple wave probe records; (ii) ocean surface images from, for example, Scanning Radar Altimeters (SRA), Synthetic Aperture Radars (SAR), or Focused Phased Array Imaging Radars (FOPAIR); and (iii) three-dimensional wave spectral specifications

3. Provide a framework for cross-calibration/validation of laboratory and field data and a quantitative assessment of the range of validity and accuracy of phase-averaged wave-prediction models

4. Investigate deterministic mechanisms for wave focusing and localization due to nonlinear wave interactions with variable currents and bottom topography using direct HOS simulations

APPROACH

An efficient high-order spectral method (HOS) for the phase-resolved simulation of nonlinear surface wave dynamics is extended to practical applications. For data assimilation and specification of the initial conditions for direct phase-resolved time simulations, an effective wave reconstruction scheme based on the multi-level iterative optimization (Wu, Liu & Yue 2000) is applied.

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HOS is a pseudo-spectral-based method that can account for nonlinear wave interactions to arbitrary high order (M). The method is extremely efficient as it obtains exponential convergence and linear computational effort with respect to the order (M) and the number of wave modes (N). HOS is an ideal approach for direct simulations of large space-time domain nonlinear evolution of wave-fields. The efficacy of HOS for the study of mechanisms of nonlinear wave dynamics in the presence of atmospheric forcing, long-short waves, finite depth and depth variations and bodies has been well established (e.g. Liu & Yue 1998).

WORK COMPLETED

The main focuses are on the study of the predictability of nonlinear irregular wave-field evolutions, and applications of phase-resolved HOS simulations to obtain direct comparisons with the classical phase-averaged model predictions of irregular wave-field developments. The specific work completed includes:

- Improvement of efficiency and robustness of HOS simulations and the wave reconstruction/forecasting scheme for the prediction of large-scale nonlinear wave-field evolutions, and implementation/validation of HOS computations on distributed-memory parallel platforms.

- Investigation of the deterministic predictability of nonlinear wave-field evolutions, application of the wave reconstruction/forecasting capability to wave-basin data, and direct comparisons of the phase-resolved simulations and wave-basin measurements of steep wave-field evolutions (Wu, Liu & Yue 2002).

- Development of effective robust filtering schemes, based on the use of the low-pass filtering (in spectral domain) and the physical-space (local) smoothing techniques, for modeling of large-scale wave breaking events in direct phase-resolved simulations of nonlinear wave-field evolutions.

- Preliminary applications of direct phase-resolved (HOS) simulations for the prediction of nonlinear three-dimensional irregular wave-field evolutions; and comparisons of the present phase-resolved predictions with the classical phase-averaged model results.

- Investigation of the nonlinear mechanisms of wave blocking and focusing by variable currents using direct phase-resolved HOS simulations.

RESULT

A significant application of the present nonlinear wave reconstruction with phase-resolved simulations is to obtain deterministic forecasting of realistic ocean wave evolution, which is of great significance to naval operations. For example, it allows the development of wave dodging schemes using path optimization and/or intelligent control/maneuvering to enhance the survivability of surface vessels in severe sea conditions. Given discrete (or continuous) wave probe data up to a certain time (say, $t \in (0,T)$), the objective of wave forecasting is to predict the evolution of the wave field in the future (say, $t \in (T,T_F)$ where $T_F > T$). To do that, we first perform wave reconstruction based on the probe data to obtain a reconstructed continuous wave field and its evolution in $t \in (0,T)$. Using the reconstructed wave field as an initial state, the phase-resolved HOS simulation will then provide a prediction of the future evolution of the wave field in $t \in (T,T_F)$. The duration of time, $T_F - T$, in which the wave field evolution can be reliably forecasted, depends on the basic characteristics of the wave field as well as

the position of the wave-field to be forecasted. Figure 1 shows a sample wave reconstruction and forecasting result for a steep long-crested wave field. For this result, wave record (from a synthetic wave field) with $\boldsymbol{T}$=71.5s at location $\boldsymbol{x}$=0 is used for wave reconstruction. As shown in figure 1a, the wave elevation of the reconstructed wave field compares well with the original probe data. At location $\boldsymbol{x_1}$=400m downstream, as shown in figure 1b, the wave elevation is excellently forecasted up to $\boldsymbol{T_F}$=122s.

Until recently, phase-averaged models such as *WAM* (for deep ocean) and *SWAN* (for near-shore regions) are the only practical tools available for the prediction of ocean wave development. These phase-averaged approaches suffer from a number of basic attributes that in fundamental and practical ways limit their ability to make major further improvements/advances in key areas. At a basic level, modeling of the phase-averaged wave action evolutions themselves, while computationally more expedient, does not allow the inclusion of physical processes in a direct mechanistic manner that can be obtained in direct nonlinear phase-resolved simulations. With recent rapid development of computational capabilities and fast direct simulations, the time and opportunity have arrived for the practice of direct phase-resolved simulations to complement phase-averaged models for ocean wave predictions. Toward this direction, in this effort, we performed large-scale phase-resolved (HOS) simulations to study the nonlinear evolution of three-dimensional wave-fields with full nonlinear wave-wave interaction effects included. Figure 3 shows a comparison between the present (preliminary) phase-resolved result and the phase-averaged method prediction (Resio & Perrie 1991) for the energy transfer rate of JONSWAP spectrum due to nonlinear wave-wave interactions. In the phase-resolved simulations, the initial three-dimensional wave field is constructed based on the JONSWAP spectrum with $\cos^2\theta$ spreading factor, and $\boldsymbol{N}=\boldsymbol{O}(10^7)$ wave modes and order $\boldsymbol{M}$=3 are used. The comparison indicates that the difference between the two approaches becomes larger as the wave steepness increases. Even for the case of small wave steepness, an apparent difference exists since the phase-averaged approach accounts for only partial nonlinear effects while the phase-resolved calculation includes all the nonlinear interactions.

IMPACT/APPLICATION

The present work is a first step toward direct computational prediction of realistic ocean wave-field evolutions without phase-average approximations. It can provide a framework for cross-calibration and validation of laboratory and field data and a quantitative assessment of the range of validity and accuracy of phase-averaged wave-prediction models. It will also be invaluable to improving our understanding and interpretation of remotely sensed sea surface images.

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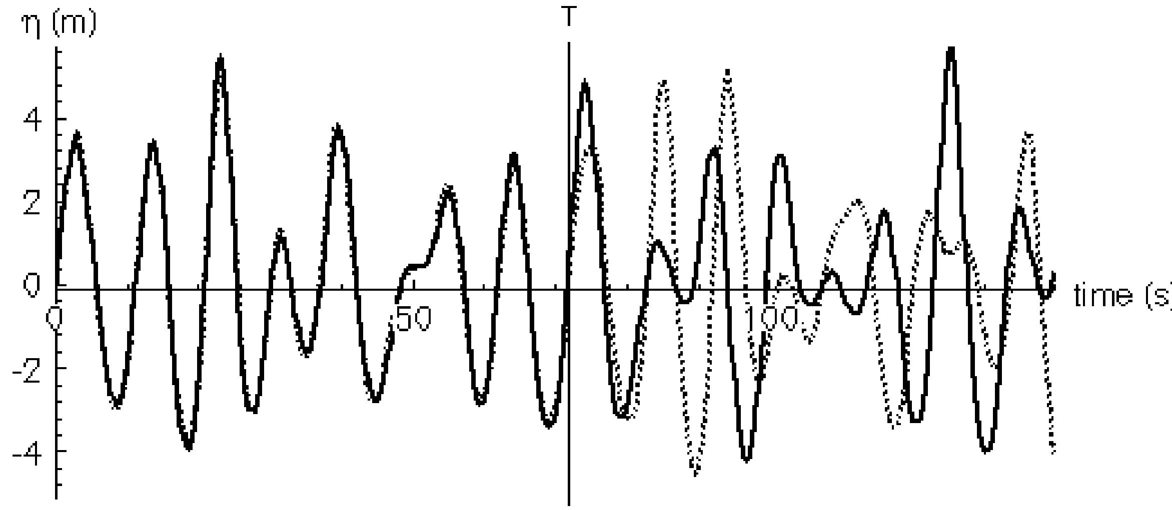
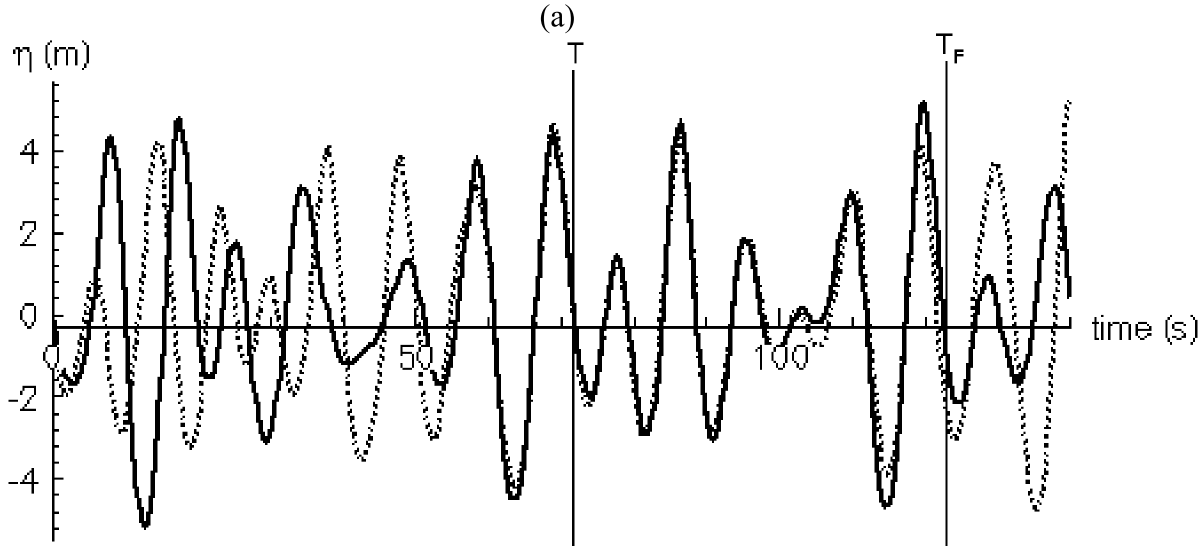
Wu, G., Liu, Y. & Yue, D.K.P. 2002 Reconstruction and forecasting of nonlinear three-dimensional irregular wave fields. *J. of Fluid Mech*. (submitted).



(a)



(b)

Figure 1. Comparison of the numerical wave reconstruction and forecasting results (- - -) and the specified wave records (—) of a long-created synthetic wave field: (a) elevation history at point x=0; and (b) wave elevation history at point x_1=400m downstream. The record in t∈(0,T) at x=0 is used for wave reconstruction while the numerical result beyond T is forecasted. The forecasted wave at x_1=400m compares well to the original data (which is not used in reconstruction and forecasting).

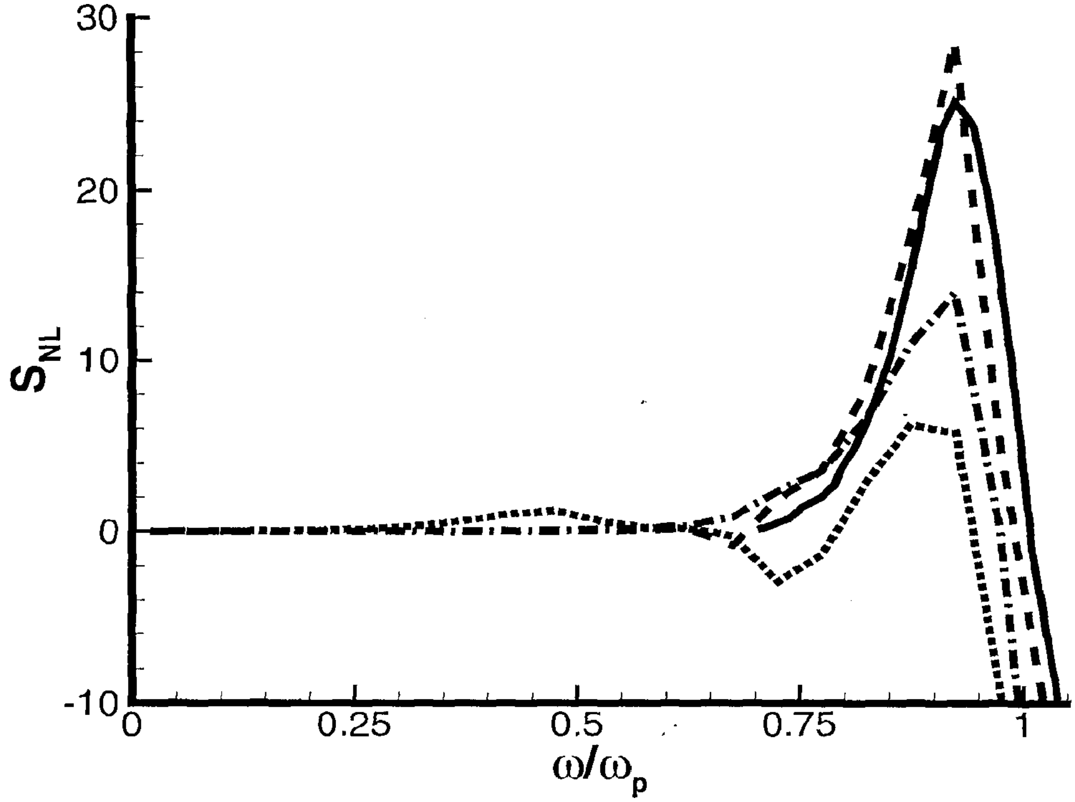


Figure 2: Energy transfer rate of JONSWAP spectrum (of a three-dimensional wave field) due to nonlinear wave-wave interactions. The plotted is the comparison of the prediction from Hasselmann's integral equation (Resio & Perrie 1991) (—) and the results from direct phase-resolved computations with different wave steepness ε ***= 0.10 (- - -), 0.15 (- · · -), and 0.20 (·····). (For clarity, only the down-shift side of the results are plotted).***